The Effect of Clock Frequency Offsets on Downlink MC-DS-CDMA

Heidi Steendam and Marc Moeneclaey
DIGCOM Research Group – TELIN Department
Ghent University – St. Pietersnieuwstraat 41 – B9000 Gent – Belgium
{hs,mm}@telin.rug.ac.be

***Abstract* - In this contribution, we investigate the effect of clock frequency offsets on the performance of multicarrier direct-sequence CDMA (MC-DS-CDMA) in the downlink, assuming orthogonal spreading sequences. Theoretical expressions are derived for the performance degradation caused by the clock frequency offset, in the presence of a multipath channel. We show that the performance degradation caused by a clock frequency offset rapidly increases for an increasing number of carriers.**

I. INTRODUCTION

During the last decade, we have witnessed a widespread deployment of wireless services (cellular telephones, wireless LAN's, ...), requiring an exchange of digital information at constantly increasing data rates. To satisfy this increasing demand for higher data rates, the data rates over the existing transmission media must be enhanced. One of the transmission techniques that have received considerable attention in the context of high data rate communications is the multicarrier (MC) transmission technique, as it combines a robustness to channel dispersion with a high bandwidth efficiency [1]-[3]. Recently, some new techniques for high data rate communications, based on a combination of the MC modulation technique and the code-division multiple access technique were proposed [4]. One of these combinations is the multicarrier direct-sequence CDMA (MC-DS-CDMA) technique, which has been considered for mobile radio communications [5]-[8].

A known drawback of multicarrier systems is their high sensitivity to a clock frequency offset between the transmitter and receiver clock. In the literature, the effect of a clock frequency offset on different multicarrier systems has been considered. It has been shown that the performance of the orthogonal frequency-division multiplexing (OFDM) system [9]-[10] and the multicarrier CDMA (MC-CDMA) system [11] rapidly degrades when the number of carriers increases. Further, it has been shown in [9]-[11] that OFDM and MC-CDMA are robust to small static offsets. In this contribution, we investigate the effect of clock frequency offsets on the downlink MC-DS-CDMA system.

II. SYSTEM DESCRIPTION

The conceptual block diagram of a MC-DS-CDMA transmitter for a single user is shown in figure 1. In MC-DS-CDMA, the sequence of complex data symbols to be transmitted at rate R_s is first split into N_c symbol sequences at rate R_s/N_c. Each of these lower rate symbol sequences modulates a different carrier of the orthogonal multicarrier system. We denote by $a_{i,k,\ell}$ the i^{th} data symbol transmitted to user ℓ on carrier k, with k belonging to a set I_c of N_c carrier indices. The data symbol $a_{i,k,\ell}$ is then multiplied with a higher rate spreading sequence $\{c_{i,n,\ell}|n=0,...,N_s-1\}$ with spreading factor N_s, where $c_{i,n,\ell}$ is the n^{th} chip of the sequence that spreads the data symbols transmitted to user ℓ during the i^{th} symbol interval. Note that the spreading sequence does not depend on the carrier index k: all data symbols that are transmitted to user ℓ during the same symbol interval are spread with the same spreading sequence. We denote by $b_{i,n,k,\ell}$ the N_s components of the spread data symbol $a_{i,k,\ell}$, i.e.,

$$b_{i,n,k,\ell} = \frac{1}{\sqrt{N_s}} a_{i,k,\ell} c_{i,n,\ell} . \quad (1)$$

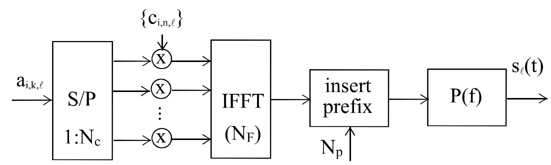

Figure 1: MC-DS-CDMA transmitter structure for one user.

The components $b_{i,n,k,\ell}$ are transmitted *serially* on the k^{th} carrier of the multicarrier system: the spreading is done in the time domain. To modulate the spread data symbols on the carriers, an N_F-point inverse fast Fourier transform (inverse FFT) is used. To avoid that the multipath channel causes interference between data symbols, each transmitted FFT block is cyclically extended with a prefix of N_p samples. This results in a sequence of samples $\{s_{i,n,m,\ell}\}$, given by

$$s_{i,n,m,\ell} = \frac{1}{\sqrt{N_F + N_p}} \sum_{k \in I_c} b_{i,n,k,\ell} e^{j2\pi \frac{km}{N_F}} . \quad (2)$$
$$m = -N_p, ..., N_F - 1$$

The sequence $\{s_{i,n,m,\ell}\}$ is fed at rate $1/T=(N_F+N_p)N_sR_s/N_c$ to the transmit filter with transfer function $P(f)$ and impulse response $p(t)$, which is a square-root raised-cosine filter with rolloff α. The resulting continuous-time complex signal $s_\ell(t)$ is given by

$$s_\ell(t) = \sum_{i=-\infty}^{+\infty} \sum_{n=0}^{N_s-1} \sum_{m=-N_p}^{N_F-1} s_{i,n,m,\ell} \cdot p\left(t - \left(m + \left(n + iN_s\right)\left(N_F + N_p\right)\right)T\right) . \quad (3)$$

It is assumed that carriers inside the rolloff area are not modulated, i.e. they have zero amplitude. Hence, of the N_F available carriers, only N_c carriers are actually modulated, i.e. $N_c \leq (1-\alpha)N_F$. The carrier index k corresponds to the carrier frequency $k/(N_FT)$.

Assuming N_c to be odd, the set I_c of modulated carriers is given by $I_c=\{0,...,(N_c-1)/2\}\cup\{N_F-(N_c-1)/2,...,N_F-1\}$. The corresponding carrier spacing Δf and system bandwidth B are given by

$$\begin{aligned}\Delta f &= \frac{1}{N_F T} = \frac{N_s}{N_c} R_s \frac{N_F + N_p}{N_F} \cong \frac{N_s}{N_c} R_s \\ B &= N_c \Delta f = \frac{N_c}{N_F T} = N_s R_s \frac{N_F + N_p}{N_F} \cong N_s R_s\end{aligned} , \quad (4)$$

where the approximation is valid for $N_p<<N_F$. Note that in this MC-DS-CDMA system, the spreading factor N_s and the number of carriers N_c can be chosen independently.

In a multiuser scenario, the basestation synchronizes the N_u user signals and broadcasts the sum of the user signals to the different users. To be able to extract the reference user signal ($\ell=0$), each user is assigned a unique spreading sequence. In this contribution, we consider orthogonal sequences that consist of user-dependent Walsh-Hadamard sequences of length N_s that are multiplied with a complex-valued random scrambling sequence that is common to all N_u users. Hence, the maximum number of users that can be accommodated equals N_s.

The sum of the different user signals reaches the receiver of the reference user through a multipath channel with transfer function $H_{ch}(f)$. The output of the channel is disturbed by additive white Gaussian noise $w(t)$ with uncorrelated real and imaginary parts, each having a noise spectral density of $N_0/2$. The resulting signal is applied to the receiver filter (see figure 2) and sampled at the instants $t_{i,n,m}+\varepsilon_{i,n,m}T$, where $t_{i,n,m}=(m+(n+iN_s)(N_F+N_p))T$ and $\varepsilon_{i,n,m}T$ denotes the deviation from $t_{i,n,m}$. Only the N_F samples with $m=0,...,N_F-1$ are kept for further processing. We assume that the length of the cyclic prefix is sufficiently longer than the duration T_{ch} of the impulse response of the composite channel with transfer function $H(f)=H_{ch}(f)|P(f)|^2$, so that each FFT block contains a segment, of duration exceeding $N_F T$, that is not affected by interference from neighboring FFT blocks (see figure 3). By means of coarse synchronization, the sample $m=0$ is located between the earliest and latest receiver timing indicated in figure 3, such that the N_F samples to be processed are free from interference from other blocks. The N_F selected samples are applied to an N_F-point FFT, yielding

$$y_{i,n,k} = \sqrt{\frac{N_F}{N_F + N_p}} \sum_{\ell=0}^{N_s-1} \sum_{k' \in I_c} b_{i,n,k,\ell} A_{i,n,k,k'} + w_{i,n,k} , \quad (5)$$

where $w_{i,n,k}$ is the additive noise component and

$$A_{i,n,k,k'} = \frac{1}{N_F} \sum_{m=0}^{N_F-1} e^{-j2\pi \frac{m(k-k')}{N_F}} H_{k'}\left(\varepsilon_{i,n,m}\right) \quad (6)$$

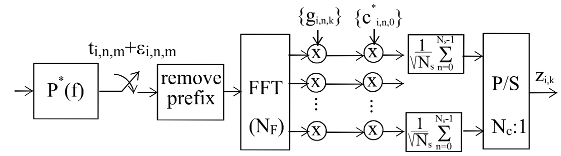

Figure 2: MC-DS-CDMA receiver structure.

$$H_k\left(\varepsilon_{i,n,m}\right) = \frac{1}{T} \sum_{m'=-\infty}^{+\infty} H\left(\frac{k}{N_F T} + \frac{m'}{T}\right) e^{j2\pi\left(\frac{k}{N_F}+m'\right)\varepsilon_{i,n,m}} . \quad (7)$$

The FFT outputs are fed to one-tap equalizers $g_{i,n,k}$ that scale and rotate the k^{th} FFT output during the n^{th} FFT block of the i^{th} symbol interval. Each equalizer output is multiplied with the corresponding chip of the reference user spreading sequence, and summed over N_s consecutive samples to obtain the samples $z_{i,k}$ at the input of the decision device:

$$z_{i,k} = \sqrt{\frac{N_F}{N_F + N_p}} \sum_{\ell=0}^{N_s-1} \sum_{k' \in I_c} a_{i,k',\ell} I_{i,k,k',\ell} + W_{i,k} , \quad (8)$$

where

$$I_{i,k,k',\ell} = \frac{1}{N_s} \sum_{n=0}^{N_s-1} c_{i,n,\ell} c^*_{i,n,0} g_{i,n,k} A_{i,n,k,k'} , \quad (9)$$

and $W_{i,k}$ is the additive noise contribution with

$$E\left[W_{i,k} W^*_{i',k'}\right] = N_0 \delta_{i-i'} \delta_{k-k'} \frac{1}{N_s} \sum_{n=0}^{N_s-1} \left|g_{i,n,k}\right|^2 . \quad (10)$$

The quantity $I_{i,k,k',\ell}$ denotes the contribution from the data symbol $a_{i,k',\ell}$ to the sample $z_{i,k}$ at the input of the decision device. The sample $z_{i,k}$ from (8) contains a useful component with coefficient $I_{i,k,k,0}$. The quantities $I_{i,k,k',0}$ ($k'\neq k$) correspond to intercarrier interference (ICI), i.e. the contribution from data symbols transmitted to the reference user on other carriers. For $\ell\neq 0$, the quantities $I_{i,k,k',\ell}$ correspond to multiuser interference (MUI), i.e. the contribution from data symbols transmitted to other users.

The equalizer coefficients are selected such that the coefficients $I_{i,k,k,0}$ of the useful components are equal to 1, for $k\in I_c$. This yields

$$g_{i,n,k} = \left(\frac{1}{N_F} \sum_{m=0}^{N_F-1} H_k\left(\varepsilon_{i,n,m}\right)\right)^{-1} . \quad (11)$$

III. Performance Analysis

The performance of the MC-DS-CDMA system is measured by the signal-to-noise ratio (SNR), which is defined as the ratio of the power of the useful component (P_U) to the sum of the powers of the ICI (P_{ICI}), the MUI (P_{MUI}) and the noise (P_N) at the input of the decision device. Note that these quantities depend on the index k of the considered carrier. This yields

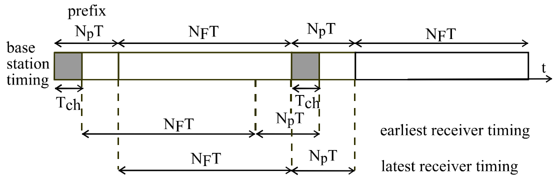

Figure 3: Earliest and latest possible timing instants at receiver that do not cause interblock interference.

$$SNR_k(\varepsilon)=\frac{\frac{N_F}{N_F+N_p}P_{U_k}}{P_{N_k}+\frac{N_F}{N_F+N_p}\left(P_{ICI_k}+P_{MUI_k}\right)}, \quad (12)$$

where

$$\begin{aligned} P_{U_k} &= E_{s_{k,0}} \\ P_{ICI_k} &= \sum_{\substack{k'\in I_c \\ k'\neq k}} E_{s_{k',0}} E\left[\left|I_{i,k,k',0}\right|^2\right] \\ P_{MUI_k} &= \sum_{\ell=1}^{N_u-1}\sum_{k'\in I_c} E_{s_{k',\ell}} E\left[\left|I_{i,k,k',\ell}\right|^2\right] \\ P_{N_k} &= N_0\frac{1}{N_s}\sum_{n=0}^{N_s-1}\left|g_{i,n,k}\right|^2 \end{aligned} . \quad (13)$$

In (13), $E_{s_{k,\ell}}=E[|a_{i,k,\ell}|^2]$ denotes the energy per symbol transmitted to user ℓ on carrier k.

In the absence of timing errors, (7) reduces to

$$H_k=\frac{1}{T}\sum_{m'=-\infty}^{+\infty}H\left(\frac{k}{N_FT}+\frac{m'}{T}\right). \quad (14)$$

The composite channel $H(f)$ is band-limited: $H(f)=0$, $|f|>(1+\alpha)/(2T)$, $0<\alpha<1$. For frequencies $k/(N_FT)$ outside the rolloff area, the sum in (14) reduces to one contribution, i.e. $H_k=H(mod(k;N_F)/(N_FT))/T$, where $mod(x;N_F)$ is the modulo-N_F reduction of x, yielding a result in the interval $[-N_F/2,N_F/2]$. Hence, for carriers outside the rolloff area, (14) equals $1/T$ times the frequency response of the composite channel $H(f)$ at the frequency $mod(k;N_F)/(N_FT)$. In addition, (6), (11) and (9) reduce to

$$A_{i,n,k,k'}=H_k\delta_{k-k'} \quad (15)$$

$$g_{i,n,k}=\frac{1}{H_k} \quad (16)$$

$$I_{i,k,k',\ell}=\delta_{k-k'}\delta_\ell . \quad (17)$$

Hence, in the absence of timing errors, the contribution of user ℓ to the k^{th} FFT output $y_{i,n,k}$ is proportional to $b_{i,n,k,\ell}H_k$, which means that intercarrier interference is absent. In addition, as the factor H_k does not depend on the chip index n, the orthogonality between the contributions from different user to the same FFT output is not affected, hence MUI is absent as well. This signifies that in the absence of timing errors, the only effect of the multipath channel is to multiply the symbols of the different users with a factor H_k, that depends on the carrier index. The presence of this factor affects the signal-to-noise ratio at the input of the decision device, but does not give rise to interference. In the absence of timing errors, the SNR in (12) is given by $SNR_k(0)=(N_F/(N_F+N_p))|H_k|^2(E_{s_{k,\ell}}/N_0)$. The degradation (in dB), caused by the timing errors is defined as $Deg_k=10log(SNR_k(0)/SNR_k(\varepsilon))$.

IV. Clock Frequency Offset

In the case that the receiver of the reference user has a free-running clock with a relative clock frequency offset $\Delta T/T$ as compared to the frequency $1/T$ of the transmitter clock, the timing deviation linearly increases in time: $\varepsilon_{i,n,m}=\varepsilon_0+(m+(n+iN_s)(N_F+N_p))\Delta T/T$. Hence, an increasing misalignment between the time-domain samples at the transmitter and the receiver is introduced. To compensate for this misalignment, the receiver performs a coarse synchronization. In this coarse synchronization, the receiver removes ($\Delta T<0$) or duplicates ($\Delta T>0$) receiver filter output samples at the boundaries of the FFT blocks, such that the N_F successive samples kept for further processing remain in the region where interference from other blocks is absent. After coarse synchronization, the resulting timing deviation can be written as $\varepsilon_{i,n,m}=\varepsilon_{i,n}+m\Delta T/T$, where $\varepsilon_{i,n}$ does not vary over the considered FFT block.

In this case, for the carriers outside the rolloff area, the quantities (9) become

$$I_{i,k,k',\ell}=C_{k,k'}R_{i,\ell}(k,k'), \quad (18)$$

where

$$C_{k,k'}=\frac{H_{k'}}{H_k}\frac{D\left(\frac{k'-k}{N_F}+\frac{mod(k';N_F)}{N_F}\frac{\Delta T}{T}\right)}{D\left(\frac{mod(k;N_F)}{N_F}\frac{\Delta T}{T}\right)} \quad (19)$$

$$D(x)=\frac{1}{N_F}\sum_{m=0}^{N_F-1}e^{-j2\pi mx}=e^{-j\pi(N_F-1)x}\frac{sin(\pi N_Fx)}{N_F\,sin(\pi x)} \quad (20)$$

$$R_{i,\ell}(k,k')=\frac{1}{N_s}\sum_{n=0}^{N_s-1}\tilde{c}_{i,n,\ell}(k,k')c^*_{i,n,0} \quad (21)$$

$$\tilde{c}_{i,n,\ell}(k,k')=c_{i,n,\ell}e^{-j2\pi\frac{(mod(k;N_F)-mod(k';N_F))}{N_F}\varepsilon_{i,n}} . \quad (22)$$

In (19), H_k is given by (14). The quantity $R_{i,\ell}(k,k')$ in (21) is the correlation between the sequences $\{\tilde{c}_{i,n,\ell}(k,k')\}$ and $\{c_{i,n,0}\}$. For $k'=k$, $C_{k,k'}=1$ and $R_{i,\ell}(k,k)=\delta_\ell$: contributions from different users that were transmitted on carrier k do not give rise to interference on the k^{th} FFT output. This also can be observed in (22): for $k'=k$, $\tilde{c}_{i,n,\ell}(k,k')=c_{i,n,\ell}$, such that the orthogonality between the users on the same carrier is not affected. However, for $k'\neq k$, $C_{k,k'}\neq 0$ and

$R_{i,\ell}(k,k')\neq 0$: contributions from different users that were transmitted on other carriers do give rise to interference on the k^{th} carrier: the orthogonality between the users and the carriers is affected by the clock frequency offset. Hence, a clock frequency offset causes intercarrier and multiuser interference.

The powers of the useful component, the intercarrier interference, the multiuser interference and the noise, considering the case of the maximum load ($N_s=N_u$) and all users having the same energy per symbol on each carrier, i.e. $E_{s_{k,\ell}}=E_s$ ($k\in I_c$, $\ell=0,...,N_s-1$), are given by

$$\begin{aligned} P_{U_k} &= E_s \\ P_{ICI_k} &= E_s \sum_{\substack{k'\in I_c \\ k'\neq k}} \left|C_{k,k'}\right|^2 X_{k,k'} \\ P_{MUI_k} &= E_s \sum_{k'\in I_c} \left|C_{k,k'}\right|^2 \left(1-X_{k,k'}\right), \\ P_{N_k} &= N_0 \frac{Y_k}{\left|H_k\right|^2} \end{aligned} \quad (23)$$

where

$$X_{k,k'} = \left| \frac{1}{N_s} \sum_{n=0}^{N_s-1} e^{-j2\pi \frac{(mod(k;N_F)-mod(k';N_F))}{N_F}\varepsilon_{i,n}} \right|^2 \quad (24)$$

$$Y_k = \left| D\left(\frac{mod(k;N_F)}{N_F} \frac{\Delta T}{T} \right) \right|^{-2}. \quad (25)$$

Note that $X_{k,k}=1$, $k\in I_c$. In (23), we observe that the sum of the powers of the ICI and MUI is independent of $X_{k,k'}$, hence of $\varepsilon_{i,n}$, i.e.,

$$P_{I_k} = P_{ICI_k} + P_{MUI_k} = E_s \sum_{\substack{k'\in I_c \\ k'\neq k}} \left|C_{k,k'}\right|^2. \quad (26)$$

In figure 4, the coefficient $X_{k,k'}$ is shown, assuming $\varepsilon_{i,n}$ is given by the expression $\varepsilon_{i,n}=\varepsilon_{i,0}+mod(n(N_F+N_p)\Delta T/T;1)$. For clock frequency offsets $\Delta T/T<<1/(N_s(N_F+N_p))$, the coefficient $X_{k,k'}$ is close to one over the whole range of k and k'. Hence, in this case, MUI is virtually absent ($P_{MUI}\approx 0$ in (23)); the interference consists essentially of intercarrier interference. For clock frequency offsets $\Delta T/T>1/(N_s(N_F+N_p))$, the coefficient $X_{k,k'}$ strongly depends on the indices k and k' ($0\leq X_{k,k'}\leq 1$), so that the interference consists of both intercarrier and multiuser interference. This can be explained as follows: when $N_s(N_F+N_p)\Delta T/T<<1$, the timing error $\varepsilon_{i,n,m}$ slowly varies over the N_s FFT blocks necessary to transmit the spread data symbols. In this case, the timing offset $\varepsilon_{i,n}$ after coarse synchronization becomes independent of the chip index n. Hence, the chips (22) after coarse synchronization are rotated over an angle that is independent of the chip index, such that the orthogonality between the spreading sequences of the different users is not affected: there is no MUI. When $N_s(N_F+N_p)\Delta T/T>1$, the timing offset $\varepsilon_{i,n}$ after coarse synchronization strongly depends on the chip index, affecting the orthogonality between the spreading sequences of the different users: the fraction of MUI to the total interference increases, and at the same time the fraction of ICI is reduced.

To clearly isolate the effect of the clock frequency offset, we consider the case of an ideal channel, i.e. $H_k=1$, $k\in I_c$. From (23) and (25) it follows that the total interference power and the noise power depend on the carrier index k. The degradation as compared to a zero clock frequency offset is given by

$$Deg_k = 10\,log\left(Y_k + SNR(0) \sum_{\substack{k'\in I_c \\ k'\neq k}} \left|C_{k,k'}\right|^2 \right), \quad (27)$$

where $SNR(0)=(N_F/(N_F+N_p))(E_s/N_0)$ is the SNR in the absence of a clock frequency offset. In figure 5, the degradation (27) is shown as function of the carrier index, for $N_F=64$, $N_c=57$, $N_F\Delta T/T=10^{-1}$ and $SNR(0)=10dB$. As we observe, the maximum degradation occurs for carriers close to the edge of the rolloff area, i.e., for $k \approx (N_c-1)/2$ and $k\approx N_F - (N_c-1)/2$. For given k, the degradation depends on the number N_c of modulated carriers, as in (27), the summation over k' ranges over the set I_c of N_c modulated carriers. An upper bound on this degradation is obtained by extending in (27) this summation interval over all N_F available carriers, i.e. $k'=0,...,N_F-1$. This yields

$$Deg_k = 10\,log\left(Y_k + SNR(0) \sum_{\substack{k'=0 \\ k'\neq k}}^{N_F-1} \left|C_{k,k'}\right|^2 \right) \quad (28)$$

This bound is also shown in figure 5, for $k = 0, ..., N_F-1$. For given k, the upper bound (28) on the degradation is independent of the number N_c of modulated carriers, and becomes maximum for the carrier $k=N_F/2$. The upper bound is reached when all carriers are modulated ($N_c=N_F;\alpha=0$). For small x, the approximation $sin(\pi x)\approx\pi x$ holds, such that $|D(x)|\approx sin(\pi N_F x)/(\pi N_F x)$ (see (20)). Hence, when $N_F>>1$, the degradations (27) and (28) are a function of $N_F\Delta T/T$ when $mod(k;N_F)/N_F$ is a fixed value. Further, in (27) and (28) we observe that the performance degradation is independent of the spreading factor. Figure 6 shows the bound (28) for $k=(N_c-1)/2$, along with the actual degradation Deg_k from (27) for $k\in I_c$, and the maximum (over k) of the actual degradation. As we observe, the bound (28) nearly coincides with the actual maximum degradation (27), and for a substantial number of modulated carriers the actual degradation is close to the maximum degradation; this illustrates the importance of the bound (28). To obtain small degradations, it is required that $|N_F\Delta T/T|<<1$, in which case the degradation is proportional to $(N_F\Delta T/T)^2$.

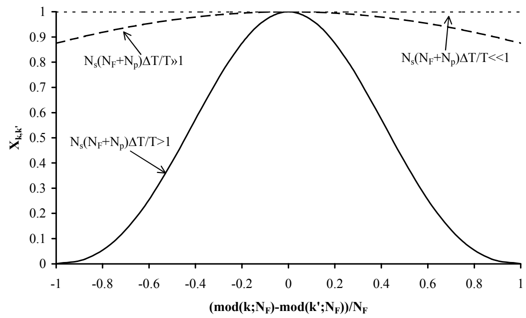

Figure 4: The coefficient $X_{k,k'}$.

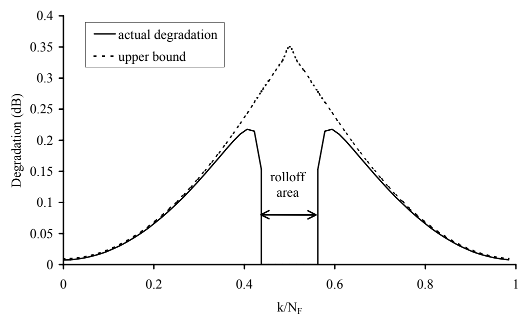

Figure 5: Degradation caused by the clock frequency offset, (N_F=64, N_c=57, $N_F\Delta T/T=10^{-1}$, $SNR(0)=10dB$).

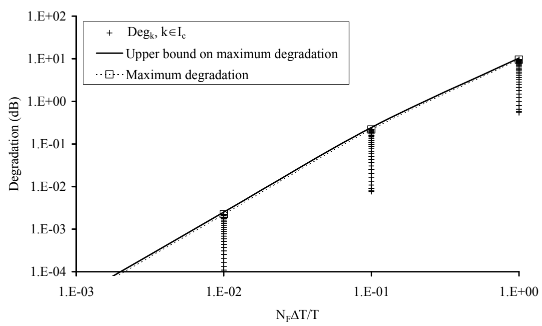

Figure 6: Maximum degradation in presence of clock frequency offset (N_F=64, N_c=57, $SNR(0)=10dB$).

In the case of a zero clock frequency offset ($\Delta T/T=0$), the timing deviation reduces to $\varepsilon_{i,n,m}=\varepsilon_0$. As $\varepsilon_{i,n,m}$ is independent of the indices m, n and i, the coefficient $H_k(\varepsilon_0)$ reduces for carriers outside the rolloff area to

$$H_k\left(\varepsilon_0\right)=H_k e^{j2\pi\frac{mod(k;N_F)}{N_F}\varepsilon_0}, \qquad (29)$$

where H_k is given by (14). As we observe in (29), the only effect of a constant timing offset is a rotation over a carrier-dependent angle $2\pi mod(k;N_F)/N_F\varepsilon_0$ of the FFT outputs. Further, the constant timing offset introduces no intercarrier interference nor multiuser interference. The systematic phase rotation of the FFT outputs can be compensated without reduction of the SNR by rotating the k^{th} FFT output over an (estimate of the) angle $-2\pi mod(k;N_F)/N_F\varepsilon_0$.

V. CONCLUSIONS AND REMARKS

In this contribution, we have investigated the effect of a clock frequency offset on the downlink performance of MC-DS-CDMA with orthogonal spreading sequences. We have pointed out that the MC-DS-CDMA system rapidly degrades in the presence of a clock frequency offset when the number of carriers increases. The degradation is largest for carriers near the edge of the rolloff area. To obtain small degradations, the clock frequency offset must be limited such that $|N_F\Delta T/T|\ll1$. The performance degradation introduced by a clock frequency offset is independent of the spreading factor. Increasing the spreading factor reduces the fraction of ICI and increases the fraction of MUI, but does not affect the total interference power.

It can be verified from [10-11] that the degradation (29) for MC-DS-CDMA is exactly the same as the corresponding degradation for OFDM and essentially the same as the degradation for MC-CDMA, assuming that the three multicarrier systems have the same carrier spacing.

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